NAS 9-14628,
T-1139, 3

NASA CR-
147591

FINAL REPORT

ON

INVESTIGATION OF STORAGE SYSTEM DESIGNS AND TECHNIQUES FOR OPTIMIZING ENERGY CONSERVATION IN INTEGRATED UTILITY SYSTEMS

VOLUME I

(EXECUTIVE SUMMARY)

MARCH 10, 1976

BATTELLE
COLUMBUS LABORATORIES
505 KING AVENUE
COLUMBUS, OHIO 43201

NAS 9-14628,
T-1139, 3

FINAL REPORT

ON

INVESTIGATION OF STORAGE SYSTEM DESIGNS AND TECHNIQUES FOR OPTIMIZING ENERGY CONSERVATION IN INTEGRATED UTILITY SYSTEMS

VOLUME I

(EXECUTIVE SUMMARY)

MARCH 10, 1976

BATTELLE
COLUMBUS LABORATORIES
505 KING AVENUE
COLUMBUS, OHIO 43201

ABSTRACT

Integrated Utility Systems (IUS) have been suggested as a means of reducing the cost and conserving the nonrenewable energy resources required to supply utility services (energy, water, and waste disposal) to developments of limited size. The potential for further improving the performance and reducing the cost of IUS installations through the use of energy storage devices was examined and the results are summarized in this report. Candidate energy storage concepts in the general areas of thermal, inertial, superconducting magnetic, electrochemical, chemical, and compressed air energy storage were assessed and the storage of thermal energy as the sensible heat of water was selected as the primary candidate for near term application to IUS.

PREFACE

This is the first of a three volume set comprising the final report on the study entitled "Investigation of Storage System Designs and Techniques for Optimizing Energy Conservation in Integrated Utility Systems." The research program was sponsored by the Urban Systems Projects Office at the National Aeronautics and Space Administration's Lyndon B. Johnson Space Center (NASA-JSC) and was performed by Battelle's Columbus Laboratories (BCL) under Contract No. NAS9-14628. The volumes are entitled

- Volume I - Executive Summary
- Volume II - Application of Energy Storage Systems to IUS
- Volume III - Assessment of Technical and Cost Characteristics for Candidate IUS Energy Storage Devices.

The contract monitor at NASA-JSC was Mr. James O. Rippey. The authors gratefully acknowledge the interest and assistance of Mr. Rippey throughout the course of the program. The BCL effort was coordinated by Mr. G. Christopher and P. Crall, principal investigator. Other contributors included Mr. Rudolfo D. Vergara (Compressed Air and Volume III editor), Dr. Eric W. Brooman (Electrochemical and Chemical), Dr. Frank Jelinek (Superconducting Magnetic), and Dr. David K. Snediker (Inertial).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Integrated Utility Systems (IUS) have been suggested as a means of reducing the cost and conserving the nonrenewable energy resources required to supply utility services (energy, water, and waste disposal) to developments of limited size. The concept brings together subsystems that serve the various utility needs into an integrated package. IUS is an extension of the familiar total energy concept in that the electrical requirements of the development or small community are generated on-site utilizing fossil-fuel fired prime movers. A portion of the waste heat rejected in the generation process is recovered and is utilized to supply space heating, space cooling (through absorption air conditioning) and domestic hot water heating requirements. IUS, however, goes beyond a conventional total energy system in that it also recovers energy from the solid waste produced by the development and provides liquid waste processing and water purification as well.

Although IUS designs may be successfully developed without the use of energy storage devices, it is recognized that energy storage offers the potential for substantially improving the energy conservation aspects of IUS and/or reducing the life-cycle costs. These advantages result from the ability of energy storage to successfully couple intermittant energy sources with out of phase intermittant energy demands.

Recognizing the potential advantages of utilizing energy storage in conjunction with IUS, NASA's Lyndon B. Johnson Space Center (NASA-JSC) initiated a competitive procurement for the study described in this report. The primary objective of this study was to identify and assess candidate energy storage systems for application to Integrated Utility Systems (IUS) and to recommend one or more systems as primary candidates for near term (minimum of development) IUS application. A secondary objective was to identify those areas where additional research and development effort could be expected to reduce the cost or improve the performance of candidate energy storage systems. The subject study was awareded to Battelle's Columbus Laboratories (BCL); procedures utilized and the results obtained are presented in a three-volume report

organized as follows:

- Volume I - Executive Summary
- Volume II - Application of Energy Storage Systems to IUS
- Volume III - Assessment of Technical and Cost Characteristics for Candidate IUS Energy Storage Devices.

Volume II is aimed primarily at technical oriented readers who are interested in the application of energy storage devices to IUS. Topics covered include (1) descriptions of the two no-storage IUS baselines utilized throughout the study, (2) discussions of the assessment criteria and selection framework utilized, (3) a summary of the rationale utilized in selecting the primary energy storage candidate (water storage) for near-term application to IUS, (4) discussion of the integration aspects of water storage systems, and (5) an assessment of IUS with water storage in alternate climates.

Volume III is a collection of monographs which discuss each of the energy storage categories assessed in the study. It is thought that this volume will not only serve as a backup reference for Volumes I and II, but also serve as an introductory work for those readers who have an interest in energy storage technology, but who have not been exposed to much of the literature in this area. Volume III, therefore, briefly covers the basic theory of operation of each of the energy storage categories and contains references which serve as a guide to the information available.

SUMMARY

The overall philosophy underlying this investigation was structured around the realization that Integrated Utility Systems can be designed and operated successfully without utilizing energy storage devices. In order to be considered, then, candidate energy storage systems must offer the potential of improving the overall performance and/or reducing the cost of the IUS. Thus, the "no-storage" constitutes a natural baseline for the comparative assessment of energy storage devices. The basic procedure utilized throughout this study was to first define two "no-storage" baseline systems which were thought to represent typical IUS applications. These baseline systems were then "perturbed" by the addition of energy storage systems and the associated results assessed.

The objectives of the study were achieved through the essentially sequencial performance of the following tasks:

- Task 1. Development of a Study Plan
- Task 2. Definition of IUS Baselines
- Task 3. Resource Collection/Classification
- Task 4. Assessment of Operational Storage Systems
- Task 5. Assessment of Developing Storage Systems
- Task 6. Assessment of Advanced Storage Concepts
- Task 7. Selection of a Primary Candidate for IUS Application
- Task 8. Assessment of Integration Aspects of Primary Candidate
- Task 9. Assessment of Primary Candidate in Alternate Climates.

Figure 1 shows the approach which was utilized. The first step, after the preparation of a study plan, was the definition of representative IUS designs which would serve as a baseline for the comparison of energy storage concepts. This task was broken down into four subtasks, the first of which consisted of the selection of the baseline configurations (Task 2.1). The next subtask (Task 2.2) involved developing a computer model of the baseline designs which would assist in comparisons of alternative energy storage concepts. Selected inputs for the computer program included the load profiles (for space heating, space cooling, hot water heating, and electricity)

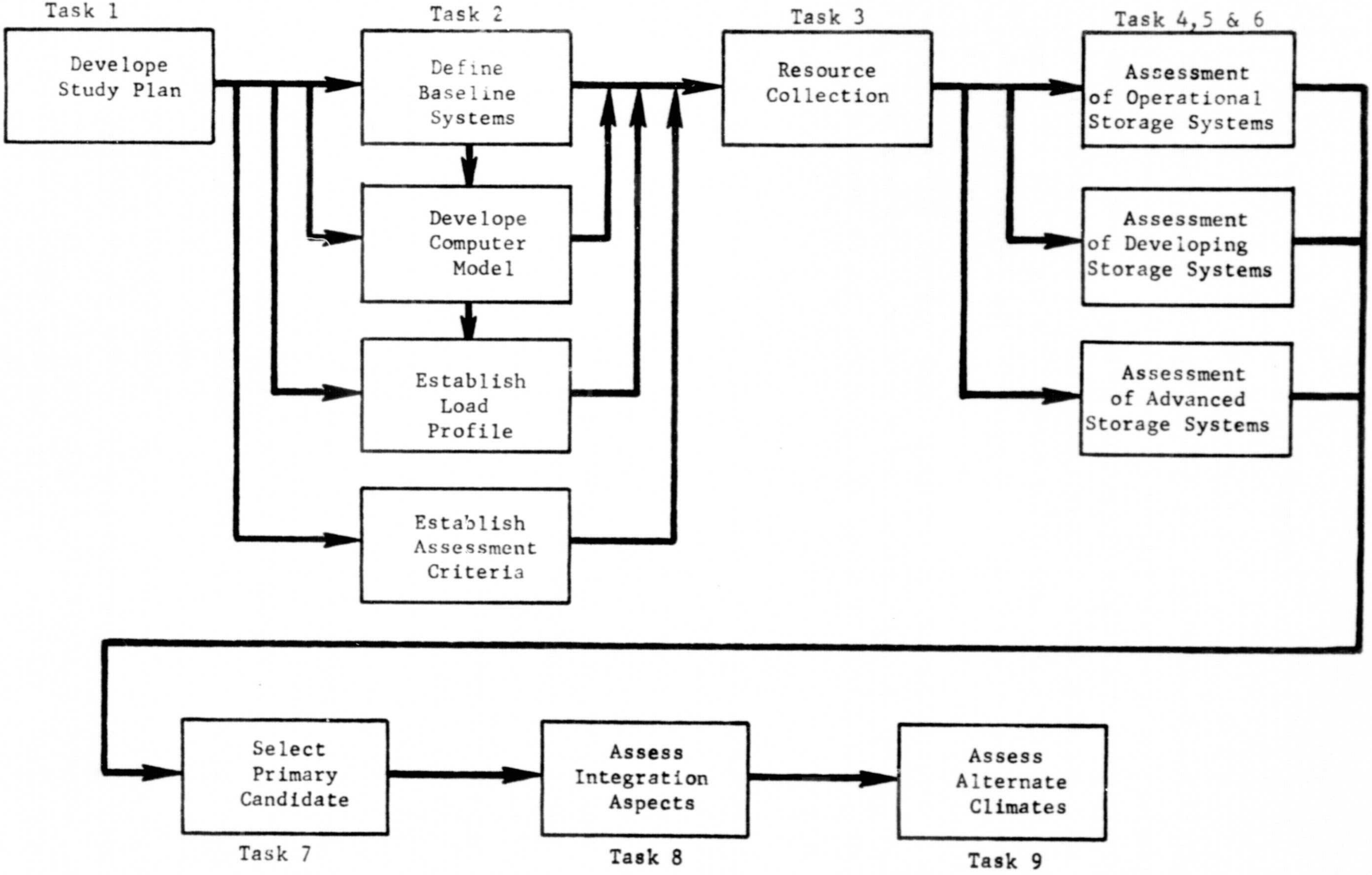

FIGURE 1. STUDY FLOW DIAGRAM

for the IUS baselines. These inputs were developed in Task 2.3 based on information supplied by NASA-JSC. The fourth subtask (Task 2.4) comprised the development of a framework for evaluating the various alternative energy storage concepts including the selection of the various criteria for assessment.

After performing an information search in Task 3, alternative energy storage concepts were assessed in Tasks 4, 5, and 6 (hereafter referred to as the "Assessment Task"). The objective of the Assessment Task was to identify energy storage concepts and to develop technical and cost characteristics for those which appeared applicable to IUS. Assessments were carried out in the general areas of

- thermal storage
- compressed air storage
- electrochemical storage
- chemical storage
- inertial storage
- superconductive magnetic storage.

The results of these tasks were then utilized in Task 7, along with the criteria for assessment developed earlier, to select a primary energy storage candidate for near term application to IUS. Integration aspects of the primary energy storage candidate were addressed in Task 8, and the effects of climate on the performance and cost of the primary storage candidate were addressed in Task 9.

The primary result of this study was the selection of thermal storage utilizing water as the primary energy storage candidate for application to Integrated Utility Systems. Water storage systems were shown to reduce the energy consumption and/or decrease the life cycle cost of all the IUS applications examined. It does not appear, however, that the magnitude of the savins is sufficient to justify the use of energy storage for all IUS installations. Other factors, such as the considerable size and construction effort required, can combine to negate the advantages of energy storage in some cases. It will

therefore be necessary to base the decision to use energy storage for a particular IUS on a careful analysis of the specific situation.

TECHNICAL DISCUSSION OVERVIEW

The investigations which were carried out in arriving at the selection of the primary energy storage candidate are summarized in the following sections.

Baseline Definition

A 1000-Unit Apartment Complex and a Village Complex were selected as the two baseline applications to be utilized throughout this study. These communities had both been examined in detail in previous studies at NASA-JSC (1,2)* and energy demand profiles were available for each. In addition, the selection of these two communities resulted in an indication of the effect of development size on the applicability of energy storage. The 1000-Unit Apartment Complex represents the low end of the size range thought feasible for IUS due to the economies of scale. The Village Complex, on the other hand, represents a longer size range and has electrical loads which are approximately an order of magnitude higher than the Apartment application. Both communities were originally assumed to be located in a region with climatic conditions similar to Washington D.C. Following identification of thermal storage (water storage) as the primary energy storage candidate the effect of alternate climates was examined by utilizing energy demand profiles representing Houston, Texas, and Minneapolis, Minnesota.

Figure 2 is a simplified block diagram depicting the energy flow in the IUS baselines. For the sake of continuity and depth, the performance characteristics of the specific equipment comprising the system were drawn, wherever possible, from the results of previous NASA-JSC studies. For example, the prime mover/generator sets for the 1000-Unit Apartments were assumed to be the same Fairbanks-Morse 478 kW diesel units which were utilized in

* Numbers in brackets indicate references listed on the last page of this volume.

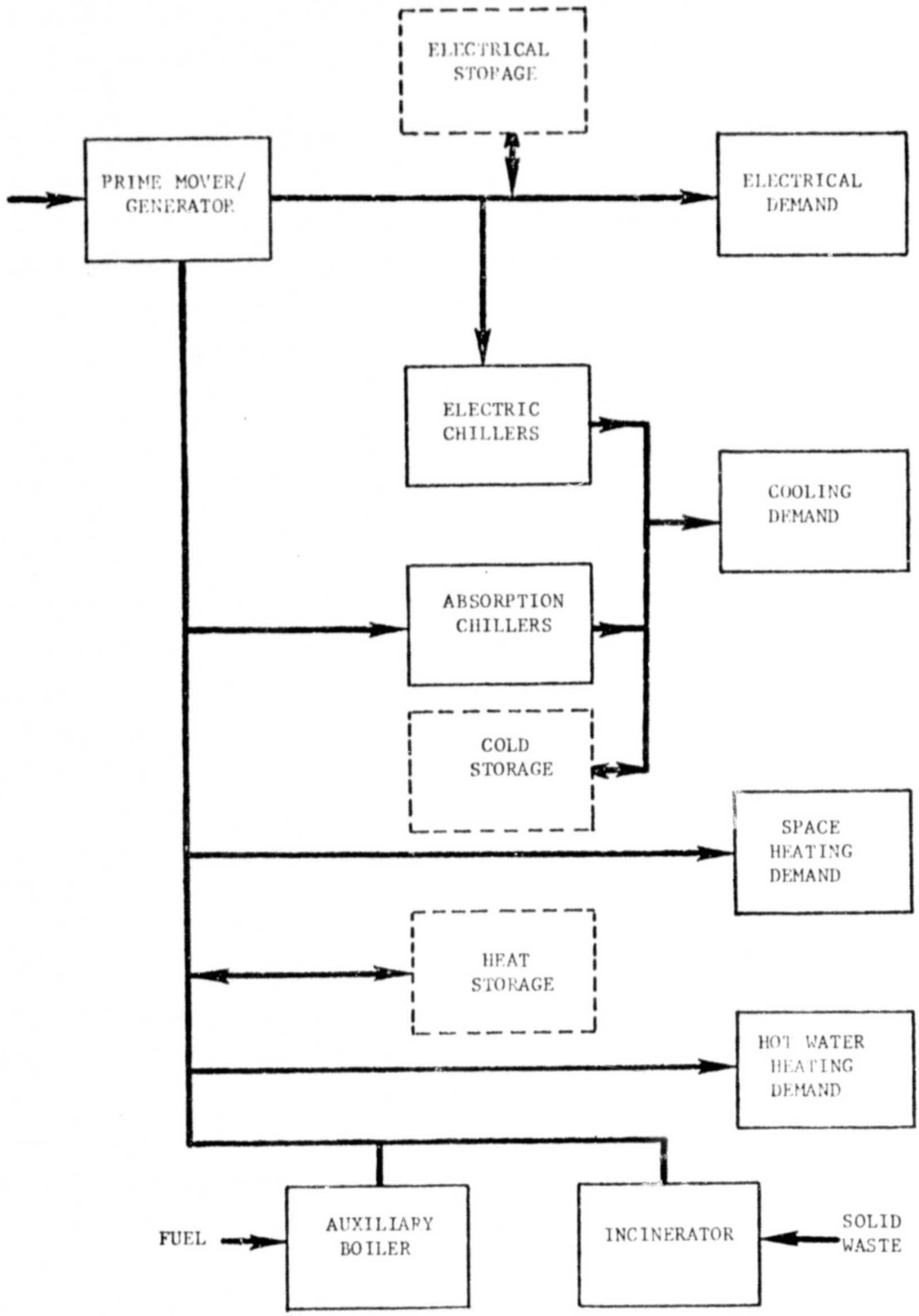

FIGURE 2. IUS BLOCK DIAGRAM

Reference 1. Likewise, the Nordberg 4415 kw diesel generator sets recommended in Reference 2 were used for the Village Complex.

The baseline, no-storage, IUS supplies the electrical requirements of the community being served via diesel generators. These units are equipped with heat recovery equipment and the recovered heat is utilized to supply space heating demands, hot water heating demands, and cooling demands (through absorption chillers). The recovered thermal energy is supplemented by a heat recovery incinerator and, when necessary, by an auxiliary boiler. When the recovered thermal energy is greater than the thermal demand, the excess heat is rejected to the atmosphere. During periods when the cooling demand exceeds the capacity of the absorption chillers, electric chillers are brought on line to satisfy the cooling load.

It has been assumed, as in previous IUS studies, that all of the electrical energy required by the baseline communities is generated on-site and that power may be drawn from a conventional utility grid only during emergencies. This is an important assumption since it results in the necessity of installing electrical generation capacity sufficient to meet the peak electrical demand.

Energy Storage System Integration

An important task which was carried out early in the study was the identification and assessment of possible methods of integration of energy storage devices with the IUS baselines. Three of the methods identified appeared to be feasible and are loosely referred to as "electrical storage", "heat storage", and "cold storage". These integration concepts are depicted by the dashed-border blocks shown in Figure 2.

Electrical Storage. Electrical storage systems* are charged by drawing electrical energy from the IUS bus bar during periods when the generation

* The term "electrical storage" is taken here to refer to the method of integration and not the form of the energy in storage. Flywheels, batteries, and compressed air may all be treated as electrical storage devices for integration purposes.

capacity is greater than the demand. The electrical energy in storage is recovered during periods when the demand exceeds the installed generation capacity. Thus, the storage system acts as a "peak shaving" device. One advantage of this mode of operation is that the generation equipment operates with a higher load factor and, therefore, a somewhat higher efficiency. Another advantage is the possible cost savings due to the reduced generation capacity required. It should be pointed out however that net cost savings will only accrue if the cost of the energy storage device is less than the cost of the generating equipment which is being replaced.

Heat Storage. Heat storage systems would be charged during periods when the thermal energy recovered from the prime mover and solid waste exceeds the requirements for space heating, space cooling, and domestic hot water heating. The systems would store thermal energy for use during periods when the thermal demand is greater than recovered thermal energy. Thus, a properly sized thermal storage system would eliminate the necessity for supplying heating loads via an auxiliary boiler. The primary advantage of heat storage is, therefore, the reduction of the energy requirements of the IUS.

Cold Storage. The final integration concept which was identified as having possible application to IUS is termed "cold" storage. The storage system would be charged during the hours when excess generation capacity is available. The excess capacity would be used to power electric chillers and the "cold" would be placed in storage. The stored energy would then be used at a later time to supply peak cooling requirements. The cold storage concept, like electrical storage, is basically a means of shaving the peaks from the electrical demand profile. The same advantages (i.e., improved load factors and reduced generation capacity required) therefore apply. Cold storage has the additional advantage of increasing the coefficient of performance of the chillers due to increased operation during periods of the day when ambient temperatures are lower.

Computer Program Development

A computer program was developed to aid in the analysis of energy storage systems imbedded in the IUS baselines. The program, entitled IUSMOD, is a modification of the ESOP computer program utilized by NASA-JSC.(3) It calculates the fuel required by prime movers and auxiliary boilers to supply the electrical, space heating, space cooling, and water heating requirements of the baseline communities. In its present form the program readily handles all three of the storage integration concepts addressed in this study--electrical, heat, and cold storage.

Inputs required by the program include the hour-by-hour demand profiles for hot water heating, space heating, space cooling, and electricity. The performance parameters for the various IUS components (boilers, chillers, etc.) are also inputs, as are the appropriate "flags" which describe the case being run. Program output consists of the calculated fuel utilization, generator output, chiller output, waste heat recovered, and energy to and from storage for each hour of the period under consideration.

The IUSMOD computer program described is a relatively simple analytical tool intended for preliminary sizing of storage schemes and rough estimates of the annual fuel utilization of alternative IUS designs. Results of the program appear to agree reasonably well with output from the original ESOP program when similar input data are used.

Assessment Criteria

In order to assist in selecting primary energy storage candidates for IUS application, a framework for carrying out the comparisons was established. The methodology utilized consisted of the selection of (1) a set of assessment criteria which were used as a basis of judging the merits of the energy storage candidates, (2) a set of weights which were thought to indicate the relative importance of each criteria, and (3) a scoring system for assigning a numerical value to each of the energy storage candidates according to how

well it satisfies each of the assessment criteria. The assessment criteria selected and the weights utilized in this study are:

	Weight
• Net relative cost	2.0
• Relative fuel utilization	1.4
• Safety	1.2
• Availability/Reliability/ Maintainability	1.1
• Hardware availability	1.1
• Environmental concerns	0.8
• Energy storage density	0.6
• Expansion capability	0.6
• Transportability	0.2

The net relative cost of an energy storage device is a measure of the economic profitability of the device and is defined as the ratio of the life cycle cost of an IUS with energy storage to the life cycle cost of a comparable IUS without energy storage. Thus, the net relative cost is a measure of the cost savings resulting from an energy storage system as compared to the no-storage option.

In a like manner, the relative fuel utilization has been defined as the annual fuel utilization of an IUS with energy storage divided by the annual fuel utilization of the no-storage option.

In keeping with the philosophy of comparing all of the energy storage candidates to the no-storage option, the scoring system was designed so that the no-storage option, by definition, received a score of 5 for each criteria. The alternative energy storage concepts were assigned a score greater than 5 if judged superior to no-storage and a score of less than 5 if judged inferior to no-storage. Numerical values were allowed to range from 1 to 9. Of the assessment criteria selected, only net relative cost, relative fuel utilization, and energy storage density are amenable to quantitative estimates. The remaining criteria require that qualitative judgement be used in assigning scores.

It should be pointed out that the relative weights and the scoring techniques used in this study were selected by the study team and then reviewed by NASA-JSC personnel. As such they represent a pooled judgment of the importance of each of the assessment criteria for near term IUS applications. It is, of course, recognized that other weights and/or scoring systems may be more appropriate for energy storage applications other than IUS or as regional or other influencing conditions change the importance of each criteria.

Assessment of Alternative Energy Storage Concepts

The first step in carrying out the assessment of the alternative energy storage concepts was to estimate the storage capacities required for the 1000-Unit Apartment and the Village Complex. This was accomplished through the use of the computer program described earlier and results are illustrated for the electrical storage integration technique in Table 1. The procedure used was to reduce the generation capacity installed in the no-storage options by incrementally removing generators. A range of round trip efficiencies* which brackets the expected efficiencies of energy storage systems was used. The sizing was performed utilizing the summer design day load profiles which represents the worst case for electrical storage devices.

Examination of the data in Table 1 reveals that the daily fuel utilization of the IUS is not affected to a great extent by the addition of energy storage. This is due to the fact that the modular nature of the generation facilities permits high generation efficiencies even at low load factors. In addition, an extra energy requirement is placed on the generation system as a result of the inefficiencies of the storage device. The net result is that the fuel utilization of the IUS is increased slightly due to the use of electrical energy storage. It therefore becomes evident that this method of energy storage will only be feasible if the installed cost of the storage device is less than the cost of the generator capacity which is replaced.

* The round trip efficiency of an energy storage device is defined as the energy withdrawn during the discharge cycle divided by the energy required during charging.

TABLE 1. SUMMARY OF ELECTRICAL ENERGY STORAGE CAPACITIES

Case No.	Number of Generators Installed	Installed Generation Capacity, kW	Storage Efficiency, Round Trip	Storage Capacity Required, kWh	Energy Withdrawn From Storage During Day, kWh	Energy Supplied to Storage During Day, kWh	Maximum Discharge Rate, kW	Maximum Charge Rate, kW	Hours of Discharge	Hours of Charge	Hours Hold	Daily Fuel Consumption, gal
					1000 Apartments							
No Storage	6	2,868	–	–	–	–	–	–	–	–	–	3,367
05A	5	2,390	50	1,493	1,056	2,112	374	887	4	4	16	3,436
05B	5	2,390	70	1,261	1,056	1,507	374	739	4	3	17	3,396
05C	5	2,390	90	1,113	1,056	1,172	374	633	4	3	17	3,373
05D	4	1,912	50	9,062	4,065	5,790	905	750	7	17	0	3,480
05E	4	1,912	60	6,761	4,065	5,790	905	750	7	17	0	3,480
05F	4	1,912	70	4,878	4,065	5,790	905	750	7	17	0	3,480
05G	4	1,912	80	4,547	4,065	5,086	905	750	7	12	5	3,433
05H	4	1,912	90	4,283	4,065	4,513	905	750	7	10	7	3,394
					Village Complex							
No Storage	8	35,320	–	–	–	–	–	–	–	–	–	38,469
07A	7	30,905	50	4,496	3,179	6,360	2,921	3,764	2	4	18	38,657
07B	7	30,905	70	3,798	3,179	4,537	2,921	3,083	2	3	19	38,546
07C	7	30,905	90	3,350	3,179	3,530	2,921	2,075	2	3	19	38,484
07D	6	26,490	50	47,582	33,638	67,301	7,696	12,762	11	7	6	40,506
07E	6	26,490	70	40,191	33,638	48,019	7,696	12,675	11	6	7	39,325
07F	6	26,490	90	35,448	33,638	37,353	7,696	12,409	11	5	8	38,675

The estimated fuel usage for each of the day types is given in Table 2 for the 1000-Unit Apartment and in Table 3 for the Village Complex. It should be pointed out that the cases referred to as thermal storage involve heat storage for the autumn, winter, and spring days and cold storage for the summer days. It is interesting to note that only thermal storage results in the reduction of IUS annual fuel utilization. The magnitude of this reduction is estimated to be about 2 percent for the 1000-Unit Apartment and about 1 percent for the Village Complex.

Technical and Cost Characteristics of Energy Storage Alternatives

The energy storage concepts which were addressed in this study were classified into six categories for the purposes of developing technical and cost characteristics. These categories were

- Thermal
- Electrochemical
- Chemical
- Inertial
- Compressed Air
- Superconducting Magnetic.

A seventh category, pumped hydroelectric storage, was not treated in this study since it was felt that the special siting requirements for these systems would by overly restrictive for applicability to IUS.

The assessment procedure which was followed for each of the energy storage categories can be summarized in stepwise fashion as follows:

(1) Identification of candidate energy storage concepts or alternative implementations in each of the energy storage categories based on a review of the literature as well as discussions with contacts in the energy storage field.

(2) Preliminary assessment of each of the identified concepts to select those which appear to be most applicable to IUS.

TABLE 2. SUMMARY OF FUEL USAGE, 1000 APARTMENTS

Case	Fuel Usage (1), thousands of gallons						
	Day Type						
	Winter Design	Summer Design	Winter Average	Spring Average	Summer Average	Autumn Average	Annual
No Storage	3.159	3.367	2.390	2.188	2.642	2.200	860
Thermal Storage (4 generators)	2.186	3.371	2.186	2.188	2.632	2.201	840
Electrical Storage (5 generators)							
η = 90%	3.159	3.373	2.390	2.188	2.644	2.200	860
η = 70%	3.159	3.396	2.390	2.188	2.644	2.200	860
η = 50%	3.159	3.436	2.390	2.188	2.644	2.200	860
Electrical Storage (4 generators)							
η = 90%	3.157	3.394	2.390	2.192	2.662	2.204	862
η = 70%	3.160	3.480 (2)	2.394	2.199	2.705	2.212	868
η = 50%	3.169	3.480 (2)	2.402	2.213	2.781	2.226	878

(1) Based on continuous days of each day type.

(2) Generator sets as operating at 100% full load at all times.

TABLE 3. SUMMARY OF FUEL USAGE, VILLAGE COMPLEX

Case	Fuel Usage (1), thousands of gallons						
	Day Type						
	Winter Design	Summer Design	Winter Average	Spring Average	Summer Average	Autumn Average	Annual
No Storage	32.3	38.5	24.0	19.9	24.6	19.7	8047
Thermal Storage (7 generators)	29.3	38.5	23.1	19.9	24.7	19.7	7975
Electrical Storage (7 generators)							
η_{RT} = 90%	32.3	38.5	24.0	19.9	24.6	19.7	8047
η_{RT} = 70%	32.3	38.5	24.0	19.9	24.6	19.7	8047
η_{RT} = 50%	32.3	38.7	24.0	19.9	24.6	19.7	8047
Electrical Storage (6 generators)							
η_{RT} = 90%	32.3	38.7	24.0	19.9	24.6	19.7	8047
η_{RT} = 70%	32.3	39.3	24.0	19.9	24.6	19.7	8047
η_{RT} = 50%	32.3	40.5	24.0	19.9	24.6	19.7	8047

(1) Based on continuous days of each day type.

(3) Generation of technical and cost characteristics for the concepts selected in Step 2.

The technical and cost characteristics for each of the energy storage concepts were developed based primarily on information drawn from the literature supplemented by discussions with equipment manufacturers and other energy storage researchers.

The details of the assessments in each of the energy storage categories are presented in Volume III of this report and are summarized in Table 4 and Table 5 for the 1000-Unit Apartment and the Village Complex, respectively. The scores presented for each of the categories correspond to the concept within each category which appears most feasible for near term application to IUS. Salient results of the assessments in each of the energy storage categories are summarized briefly in the following sections.

Thermal. Four thermal storage concepts were identified which appeared to be particularly applicable to IUS. These were water storage, annual cycle ice storage, thermal wells, and a paraffin-water "hybrid" system. Of these, water storage, ice storage, and the paraffin system could operate as both heat storage systems during the heating season and cold storage during the cooling season. The thermal well concept would operate only as a heat storage system.

The results of the assessment reveal that the water storage concept is superior to the other thermal concepts treated. Key characteristics of the water storage system are reported in Tables 4 and 5. Water appears to be particularly attractive for the near term due to the relatively well developed technology available for utilizing this system. While water storage cannot be considered an "off-the-shelf" item, workable water storage systems have been constructed and it is believed that a successful design for IUS applications could be achieved.

Of the remaining concepts, the paraffin system offers the potential for reducing the size of the storage tank required but the cost of these systems appears to be excessive unless low cost paraffin containers can be developed.

TABLE 4. SUMMARY OF SCORING FOR SELECTION OF PRIMARY E/S CANDIDATE FOR 1000-UNIT APARTMENT IUS

Criteria	Weight	Energy Storage Alternative, raw score: No Storage	Electrochemical	Chemical	Compressed Air	Inertial	SMES	Thermal
Net Relative Cost	2	5	4	2	5	2	1	7
Relative Fuel Utilization	1.4	5	5	5	5	5	5	7
Safety	1.2	5	3	3	5	3	3	5
Availability/Reliability/ Maintainability	1.1	5	3	5	5	3	7	5
Hardware Availability	1.1	5	3	3	3	3	1	4
Environmental Concerns	0.8	5	5	5	3	5	3	5
Energy Storage Density	0.6	5	3	3	1	3	4	2
Expansion Capability	0.6	5	7	5	3	5	3	3
Transportability	0.2	5	5	5	3	3	3	3
Total Raw Score		45	38	36	33	32	30	41
Total Weighted Score		45	36.2	33.2	37.2	30.6	28.6	47.3

TABLE 5. SUMMARY OF SCORING FOR SELECTION OF PRIMARY E/S CANDIDATE FOR VILLAGE COMPLEX IUS

Criteria	Weight	Energy Storage Alternative, raw score: No Storage	Electrochemical	Chemical	Compressed Air	Inertial	SMES	Thermal
Net Relative Cost	2	5	5	2	5	4	2	7
Relative Fuel Utilization	1.4	5	5	5	5	5	5	6
Safety	1.2	5	3	3	5	3	3	5
Availability/Reliability/ Maintainability	1.1	5	3	5	5	3	7	5
Hardware Availability	1.1	5	3	3	3	3	1	4
Environmental Concerns	0.8	5	5	5	3	5	3	5
Energy Storage Density	0.6	5	3	3	1	3	4	2
Expansion Capability	0.6	5	7	5	3	5	3	3
Transportability	0.2	5	5	5	3	3	3	3
Total Raw Score		45	39	36	33	34	31	40
Total Weighted Score		45	38.2	33.2	37.2	34.6	30.6	45.9

Electrochemical. The four electrochemical storage systems which were selected for assessment are (1) lead dioxide-lead (or lead-acid batteries), (2) zinc-chlorine hydrate, (3) lithium-metal sulfide, and (4) sodium-sulfur systems. Of these, only the lead dioxide-lead systems are avialable for near term applications and the characteristics of this concept are presented in Tables 4 and 5. The other systems examined offer promise for reduced cost and improved performance but substantial development effort is required to obtain these benefits.

Chemical. Chemical energy storage devices utilize electrical energy for the production of a fuel (e.g., hydrogen). The fuel is stored until the storage system is called upon to produce power. The fuel is then reconverted to electrical energy. While the overall process is recognized to possess low efficiency, chemical storage concepts were examined in order to assess the potential possibility of attractive cost characteristics. The concept which was used in generating the scores shown in Tables 4 and 5 consisted of a water electrolyzer for the production of hydrogen, a high pressure steel tank storage system, and a fuel cell conversion system.

Inertial. Inertial (i.e., flywheel) storage systems store mechanical energy as a rotating mass. The primary inertial storage concept identified in the assessment task consisted of a modular arrangement with a gang of several wheels connected to a common transmission and generator. The wheels would be mounted with a horizontal spin-axis and would be contained in underground vaults for safety purposes. The wheel design selected consists of a multi-rim configuration utilizing composite materials. The near-term inertial storage system which is characterized in Tables 4 and 5 would utilize ball or roller bearings. It has been predicted that these bearings will require replacement at about one year intervals and involve considerable expense. Advanced bearing systems offer the potential for increasing the overhaul period by a factor of 10.

Compressed Air. Compressed air storage systems appear to be attractive from the standpoint of low cost but the application of these systems to IUS would appear to be minimal due to the requirement for suitable sites. The system

characterized in Tables 4 and 5 utilizes a hard rock excavated cavity as the storage vessel. The possibility of utilizing fabricated steel vessels and thereby removing the site restrictions was examined but it was determined to be uneconomical.

Superconductive Magnetic. The superconductive magnetic energy storage (SMES) device identified and assessed in this study consists of a solenoid coil configuration with cold reinforcement. It should be pointed out that SMES systems of the size under consideration have not been built and a significant amount of research and development is required before these systems may be implemented. Cost projections indicate that these systems are better suited to much larger energy storage capacities than are required for IUS and they do not appear to be cost competitive with other energy storage concepts for this application.

Selection of Primary Candidate

Careful review and integration of the results of the assessment task (especially those summarized in Tables 4 and 5) lead to the selection of water storage as the primary candidate for energy storage in connection with near term IUS application.

As indicated by the scores for the net relative cost criteria, water storage is the only storage concept examined which exhibits significant dollar savings on a life cycle basis. The scoring scale for this criteria was based on increments of 1 percent. A score of 6 for net relative cost would therefore indicate a savings of about 1 percent of the life cycle cost of the no-storage baseline IUS. A score of 4 indicated that the IUS with energy storage costs 1 percent more than a no-storage IUS.

Water storage systems also scored high in relative fuel utilization. While other storage systems (i.e., paraffin storage and thermal wells) could equal the energy savings associated with water storage, none was found to exceed it. As for net relative cost, the increment taken for scoring relative fuel utilization was 1 percent with a score of 6 corresponding to savings in energy of about 1 percent over the no-storage baseline.

Disadvantages of water storage systems can be attributed to their large size, their somewhat limited expansion capability, and the extensive on-site construction effort which is required. In addition, water storage systems are penalized slightly compared to the no-storage option because they are not considered off-the shelf items and must be designed for each specific application.

Assessment of Primary Candidate in Alternate Climates

Water storage was selected as the primary energy storage candidate as a result of an analysis of IUS baseline systems with climates similar to Washington, D.C. The effect of alternate climates on the performance of water storage systems was assessed through the use of load profiles for a 1000-Unit Apartment Complex in Houston, Texas, and Minneapolis, Minnesota. Unfortunately, the profiles for these locations corresponded to a slightly different community model than was assumed for the Washington area. Direct comparisons were therefore not possible. The results indicated, however, that water storage will be economically profitable in both of the additional locations. The Houston installation, however, will be profitable only in that the savings resulting from reduced generator capacity are greater than the installed cost of storage. The annual fuel savings resulting from the installation of water storage in the Houston area appears to be negligible. For the Minneapolis case, the annual fuel savings due to energy storage is estimated to be about 3 percent (as compared to about 2 percent for the Washington, D.C. case) and, therefore, installation of thermal storage appears to be more favorable for a Minneapolis location than for a Houston location.

CONCLUSIONS

As a result of the investigations carried out in this study, the following conclusions may be drawn:

(1) Thermal storage utilizing the sensible heat of water is the primary near-term candidate for energy storage in IUS.

(2) Water storage systems appear to be economically feasible for all of the diverse size and location IUS applications examined in this study.

(3) With the exception of thermal storage, all of the candidate storage approaches tended to increase annual fuel consumption of IUS. It appears that the primary incentive for incorporating any of the candidate energy storage systems will be that they permit a reduction in the required generating capacity and, therefore, the life-cycle costs.

(4) Thermal storage systems show potential for reducing energy consumption and/or decreasing the life cycle cost of the candidate IUS applications. The magnitude of the dollar savings associated with the installation of water storage, however, does not appear to be sufficient to justify water storage for all applications.

(5) Electrical storage systems (e.g., flywheels, batteries, compressed air, superconducting magnetic, and chemical) do not appear to be applicable to near-term IUS.

(6) Other thermal storage concepts, such as paraffin storage, appear to have advantages over water storage but significant development work is required to reduce the cost and further define the performance of these systems.

(7) Water storage systems appear less favorable as the ratio of an installation's electrical load to thermal load increases.

(8) The economic profitability of energy storage devices for IUS application appears to be relatively insensitive to changes in assumed discount rates and fuel escalation rates.

(9) The round trip efficiency of electrical storage devices, due to the low usage factor of these devices imbedded in IUS, does not appear to have a significant impact on the viability of these devices.

RECOMMENDATIONS

The following recommendations are advanced and are aimed at further improving the feasibility of thermal storage systems.

(1) Design studies should be undertaken aimed at reducing the cost of large water storage tanks suitable for IUS application.

(2) More detailed computer simulations should be developed to aid in determining the applicability of thermal storage to specific projects. The advanced program should be able to treat such factors as pumping energy requirements, variable chiller COP, detailed control logic, and precise heat losses.

(3) Investigations into methods of reducing the cost and further defining the performance of paraffin storage systems should be undertaken.

(4) Additional studies should be carried out aimed at optimizing send-out and return temperatures for the hot and chilled water distribution systems. These studies should consider storage size, chiller performance, and distribution system heat gains/losses.

VOLUME I REFERENCES

(1) NASA - Urban Systems Project Office Report, "Preliminary Design Study of a Baseline MIUS System," April, 1974.

(2) NASA - Urban Systems Project Office Report, "MIUS Community Conceptual Design Study," April, 1974, Preliminary Draft.

(3) Stallings, R. D., Ferden, S. L., Riley, E. S., "Energy Systems Optimization Program (ESOP) User's Guide - Update IV," TM4084, LEC5041, Lockheed Electronics Co., November, 1974.